Iterative Detection for Multi-User MIMO Systems

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Abstract Multi-input multi-output (MIMO) systems can serve as the building blocks for spectrally efficient mobile multi-user tactical wireless systems; however, care must be taken to translate high per-link spectral efficiency into high network throughput. Mobile tactical networks generally have several features that complicate achievement of high multi-user MIMO spectral efficiency, including non-centralized, infrastructure-free operation, and operation when all nodes are mobile, as well as requirements to minimize probability of interception and susceptibility to jamming. The paper presents results from both simulations and an extensive over-the-air measurement campaign, which illustrate the key features needed for spectrally efficient multi-user MIMO systems.

High MIMO network throughput can be achieved by combining efficient MAC (taking into account MIMO signal processing resources) and transmitter stream control, as well as high performance MIMO signal processing and waveforms that minimize per-link signal-to-interference-and-noise ratio (SINR) requirements leading to effective spectral reuse. Iterative detection schemes provide such high spectral efficiency at low SINRs, achieving performance that approaches the Shannon bound, and provide scalable complexity. These methods are also well suited to operation in multi-user environments, supporting both interference-mitigation and joint detection approaches.

The paper provides analysis and experimental results for waveforms and receiver signal processing for Space-Time Bit Interleaved Coded Modulation using multi-carrier waveforms. Results and parameter trades are presented for variations of this approach using List Sphere Detection and Soft-Symbol Cancellation as well as structures based on convolutional codes and turbo codes.

In June–September 2003, these waveforms and iterative detection methods were demonstrated over the air using a 6-element transmitter and 8-element receiver system as well as configurations using two 3-element MIMO transmitters with an 8-element receiver. The measurements provide over-the-air performance results in a variety of channel configurations and provide data on real-world multi-user MIMO radio channels.

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Performance from Experience

Iterative Detection for Multi-User MIMO Systems

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Outline

- MIMO Review
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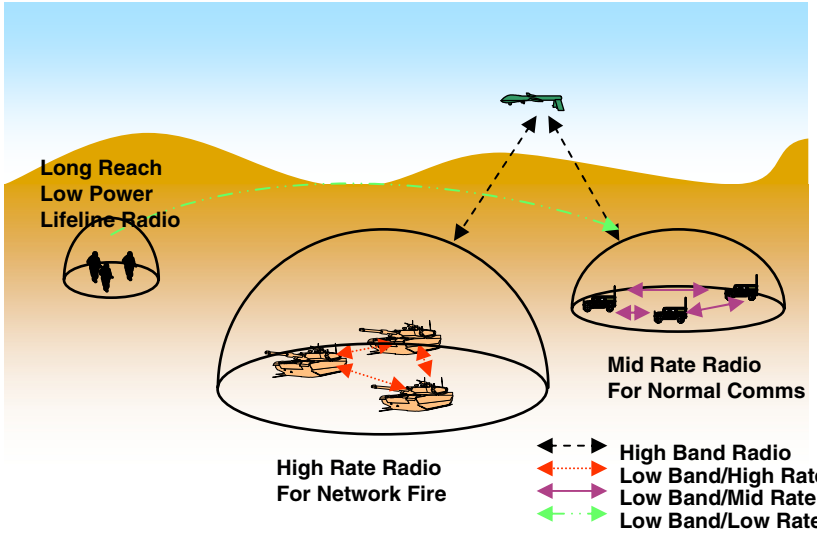
- Spring 2002 Measurements
  - OFDM STTC Waveform Spec
  - ML vs LST Results
- Waveforms for Space-Time Bit Interleaved Coded Modulation
  - Motivation
  - Designing for Iterative Detection
- Spring 2003 Multi-User MIMO Measurements
  - Channel Characterization



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MIMO Capacity Relative to Beamformed Systems

How does it compare with more traditional smart antenna techniques?

The capacity of a MIMO link is:

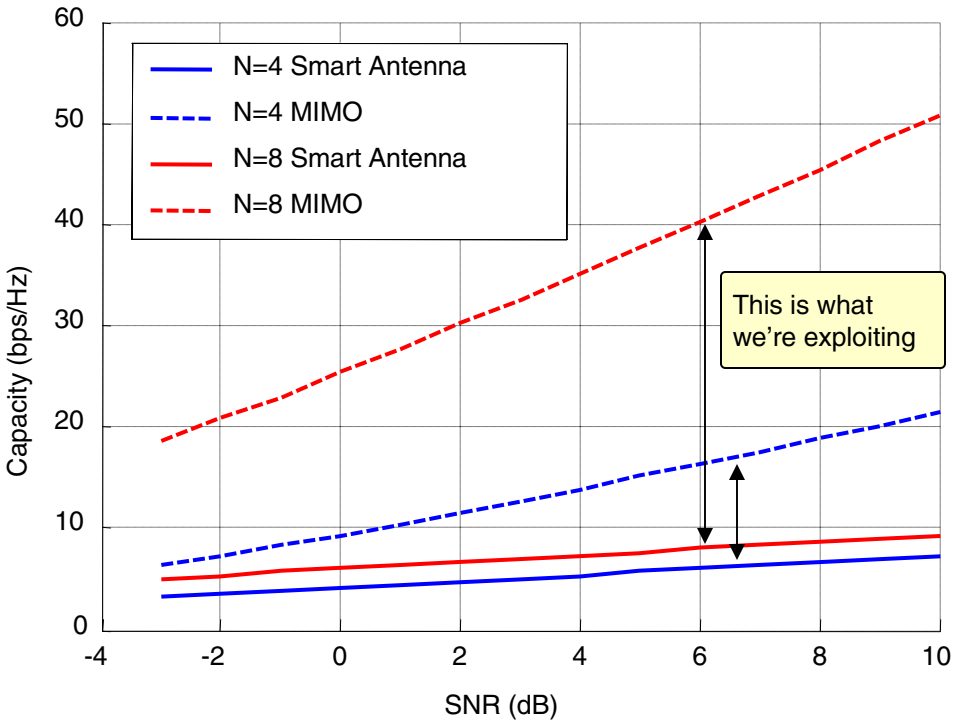
$$C = \log_2\left(\det\left(\mathbf{I}_{N_r} + \rho\mathbf{H}\mathbf{H}^H\right)\right) = \sum_{n=0}^{N_t-1}\log_2\left(1+\rho\lambda_n\right) \rightarrow N_t \log_2\left(1+\rho N_r\right)$$

Compare this with the capacity of a traditional smart antenna link:

$$C = \log_2\left(1+\rho N_t N_r\right)$$

By creating multiple parallel channels out of the multipath environment, we can obtain link efficiency that far exceeds what we can get by simply using the antenna elements for traditional beamforming.
However, this plot is overly optimistic because:

- It assumes the channel is full rank
- It assumes all paths have the same gain



ρ=SNR Per Tx antenna Per Rx antenna

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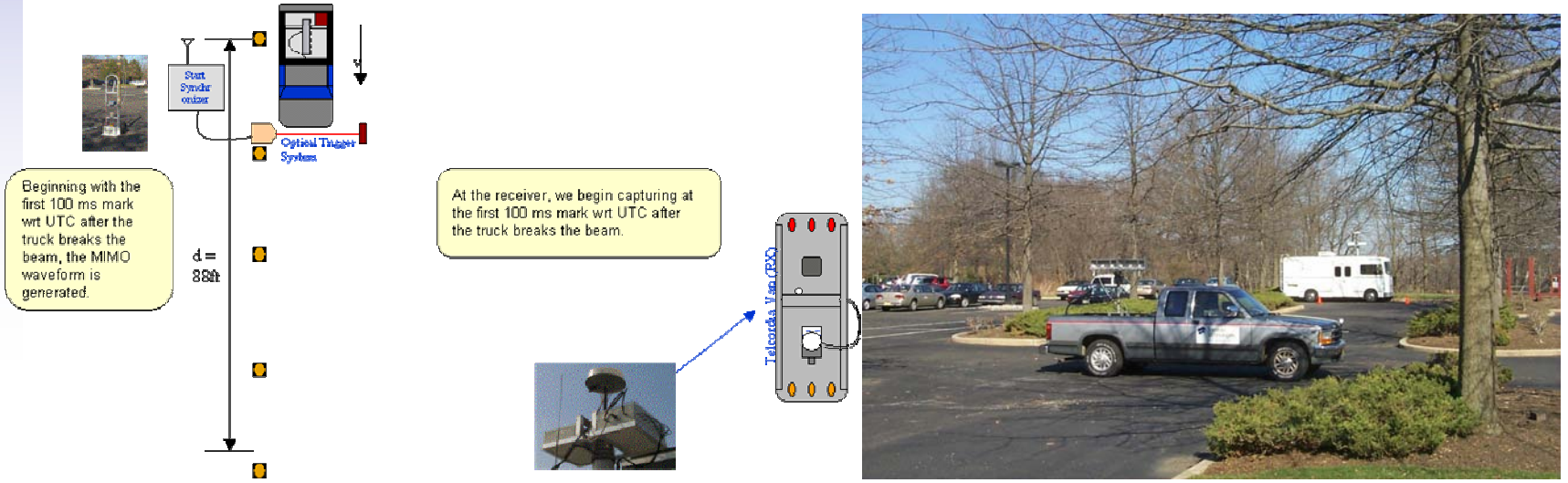
Telcordia's MIMO Experiments

- 2000: 6x8 OFDM MIMO experiment, supported by ARL
- 2001: Mobile 6x8 OFDM MIMO experiments supported by DARPA
- 2002: Demonstration of ML-detection of Space-Time Trellis Coded (STTC) OFDM MIMO over-the-air and shows improved performance relative to Layered Space Time approach (ARL).
- 2003: Demonstration of Turbo MIMO approach with soft cancellation over-the-air in joint measurements with ARL



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Spring 2002 Measurements

- Demonstrated OFDM MIMO using 4 transmitters
- Encoding and detection methods:
  - Space Time Trellis Code
  - Vector Viterbi Receiver
  - Dynamic Grouping
- Measurements through foliage and building-obstructed environments.
- Using over-the-air data, demonstrated relative performance of:
  - Layered Space Time Processing
  - Maximum Likelihood Processing
  - Dynamic Grouping with ML on Sub Groups
- Explore real-world training/sync/channel estimation

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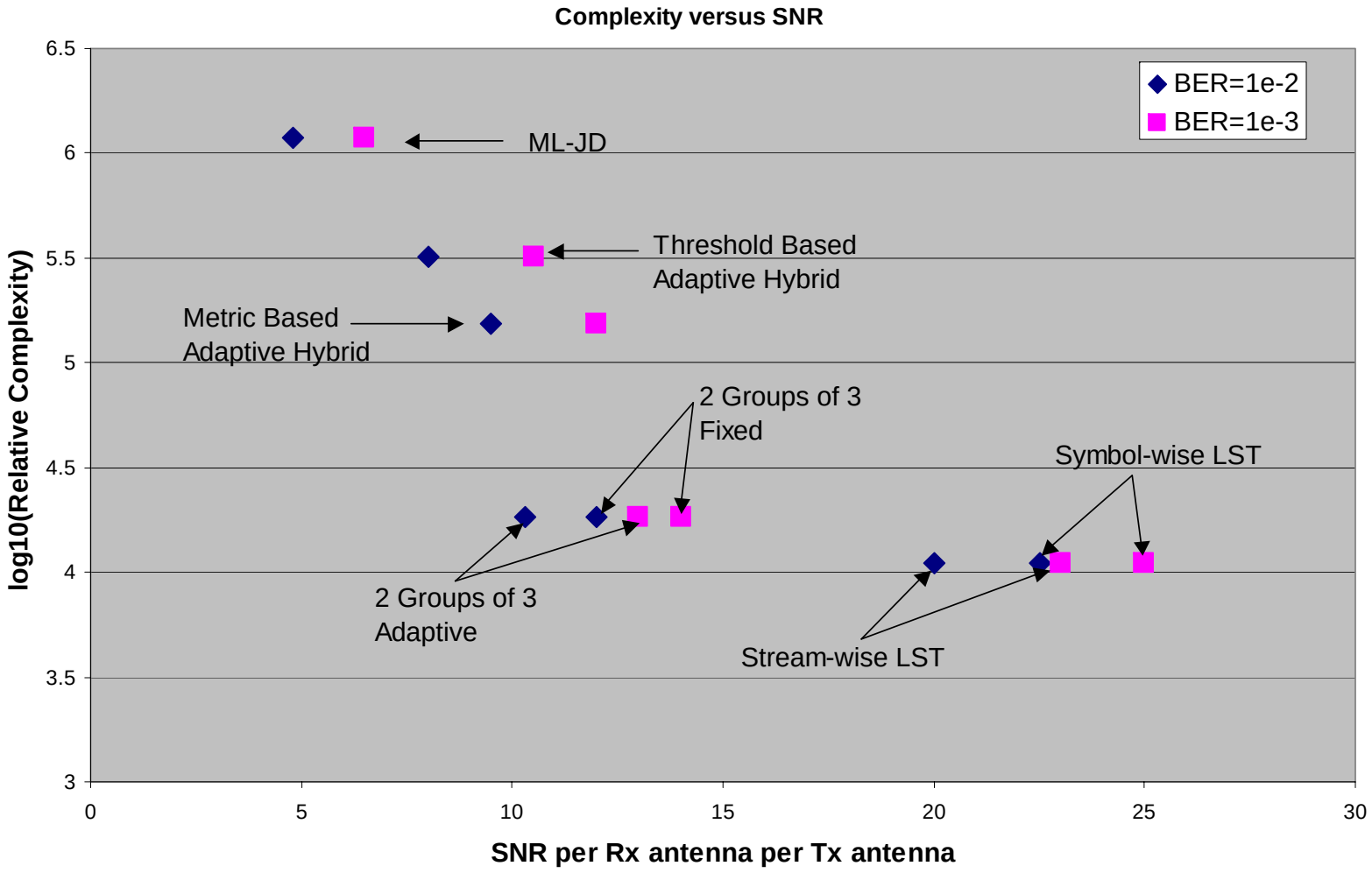
Complexity versus SNR Comparison



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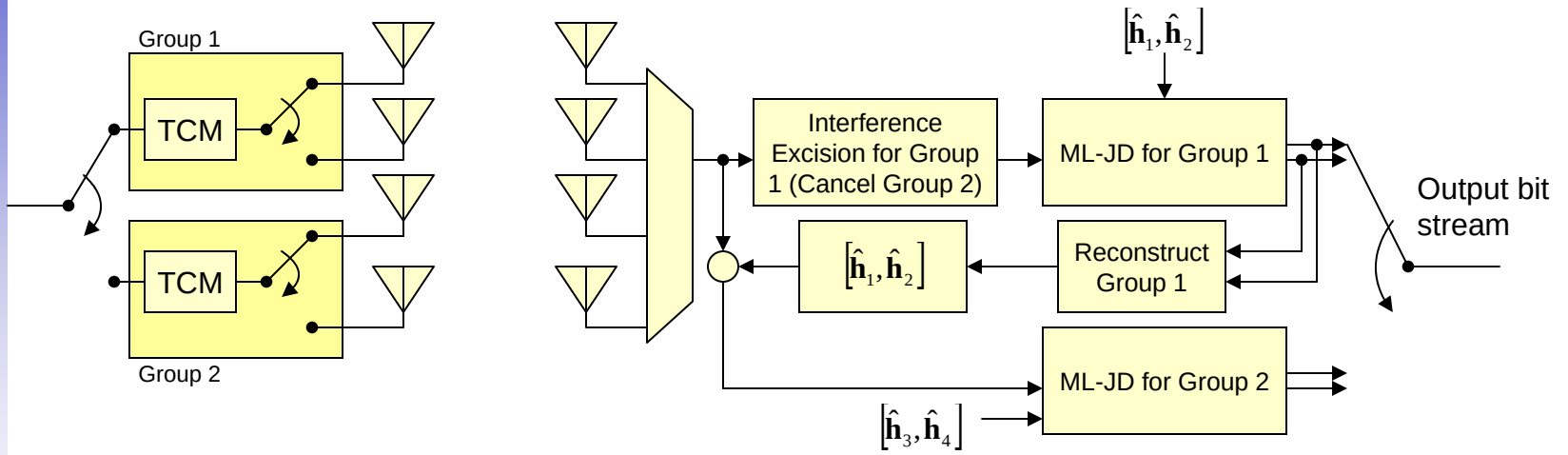
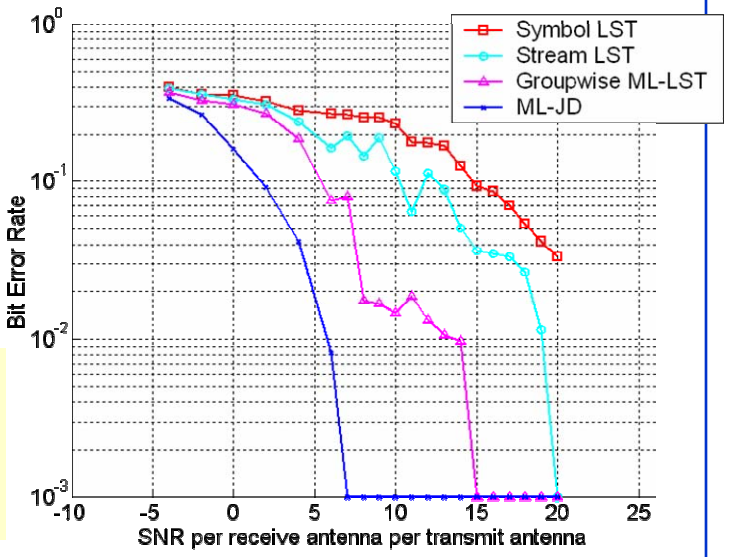
Lower Complexity Methods

Tarokh, Naguib, Seshadri, and Calderbank proposed a technique in [Tar99a] in which transmitters are grouped, with Space-Time Coding performed on groups of antennas.



The complexity of this approach is exponential in the number of antennas per group, linear in the number of groups. Therefore, the the simulation shown at right, with N_t=6, N_r=6, we obtain performance somewhere between LST and ML-JD at complexity comparable to ML-JD with N_t=3, N_r=6.



Simulation for N_t=6, N_r=6, with two groups of three transmitters.

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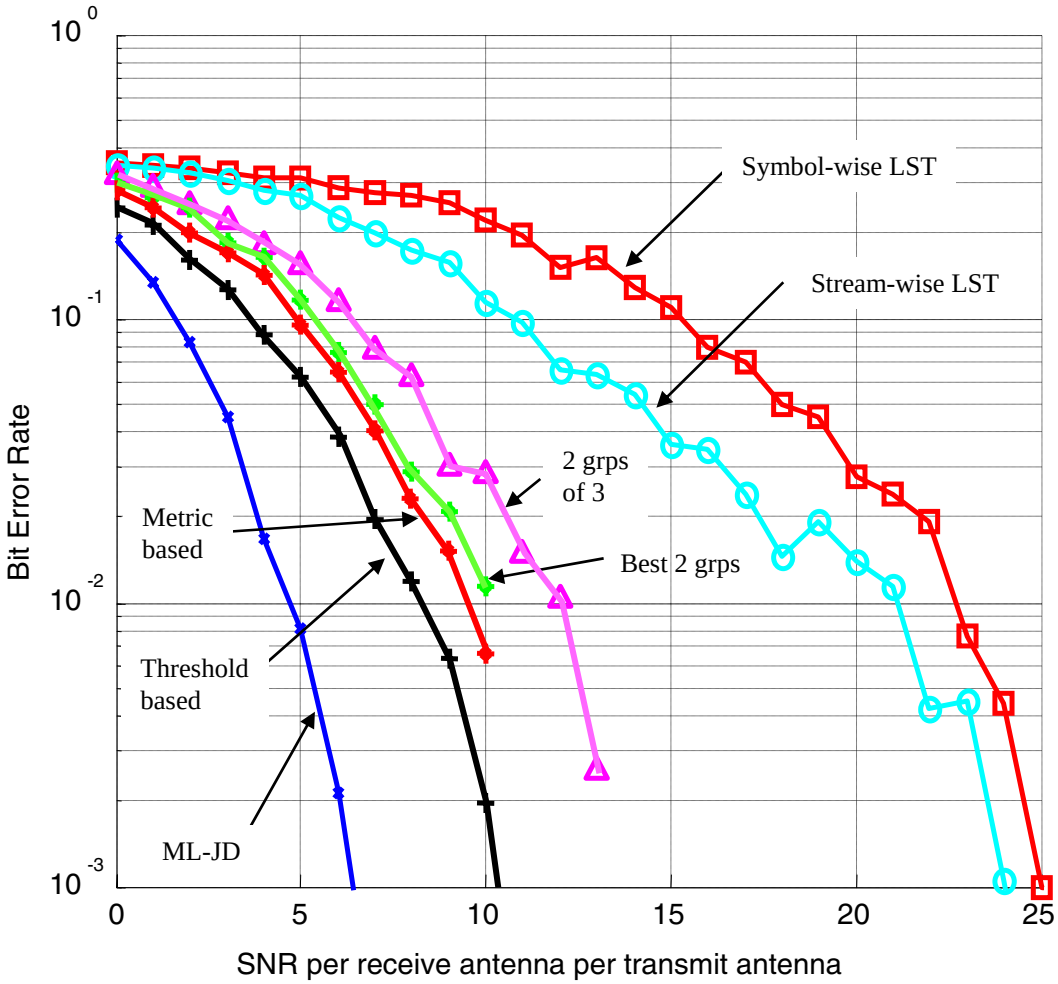
BER Comparison (6×6)



- **Threshold based technique outperforms the metric-based technique.**
  - **Threshold based allows a single group of N_t antennas (same as full ML-JD), which results in higher complexity.**
- **Since metric uses pair-wise projections, it can not produce a single group.**

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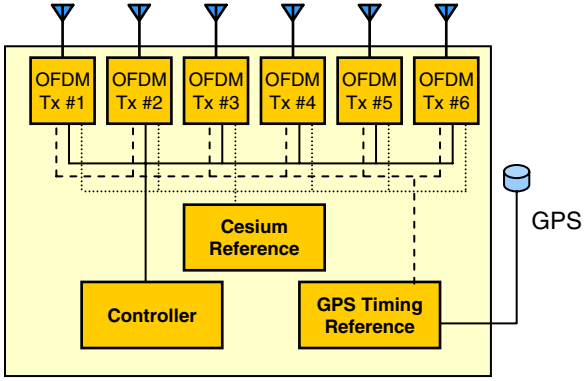
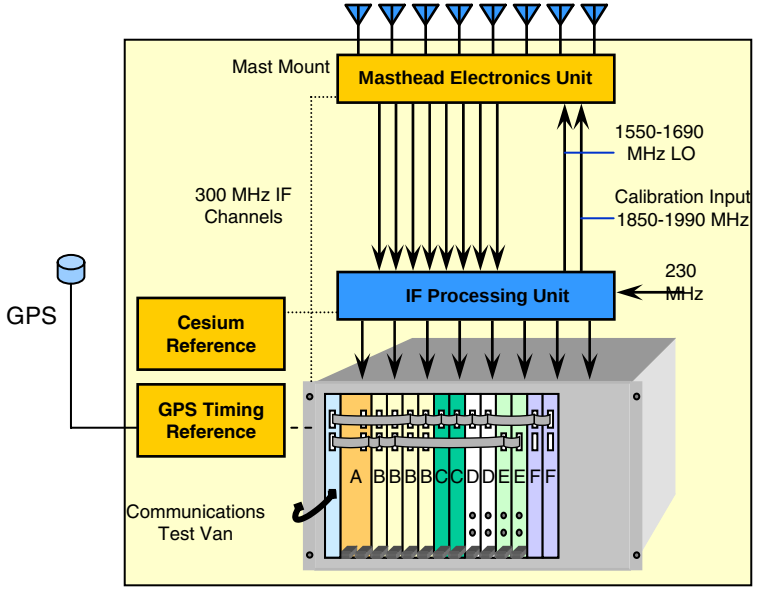
MIMO Testbed Hardware

The transmitter and receiver are shown during measurements at the RVR site.

RF Frequency:	1780-2000 MHz
Transmit Channel:	1-6 Antennas
Waveform:	192-OFDM 1.0 MHz
Receiver Channels:	8 Coherent
Rx Sampling Rate:	21.3333 Msps
A/D Conversion:	At 5.3333 MHz IF
A/D RF Bandwidth:	1.3 MHz
Array Geometry:	Circular
Mast Height:	13-46 ft.
Capture Length:	0.5 Seconds at 5.3333 Msps
Processors:	16 x 200 MHz C6201



Transmitter



Receiver

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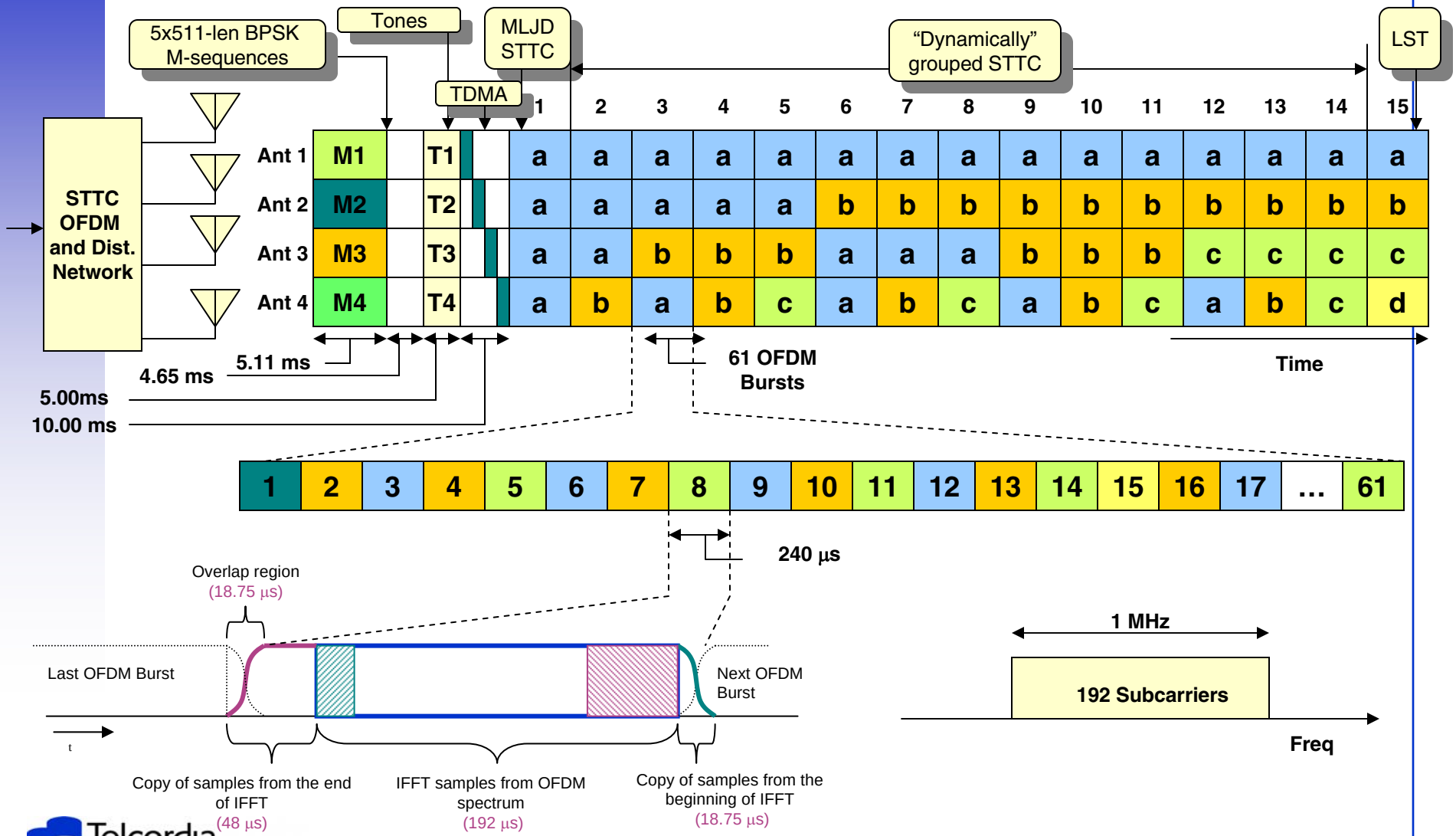
Spring 2002 OFDM STTC MIMO Measurements



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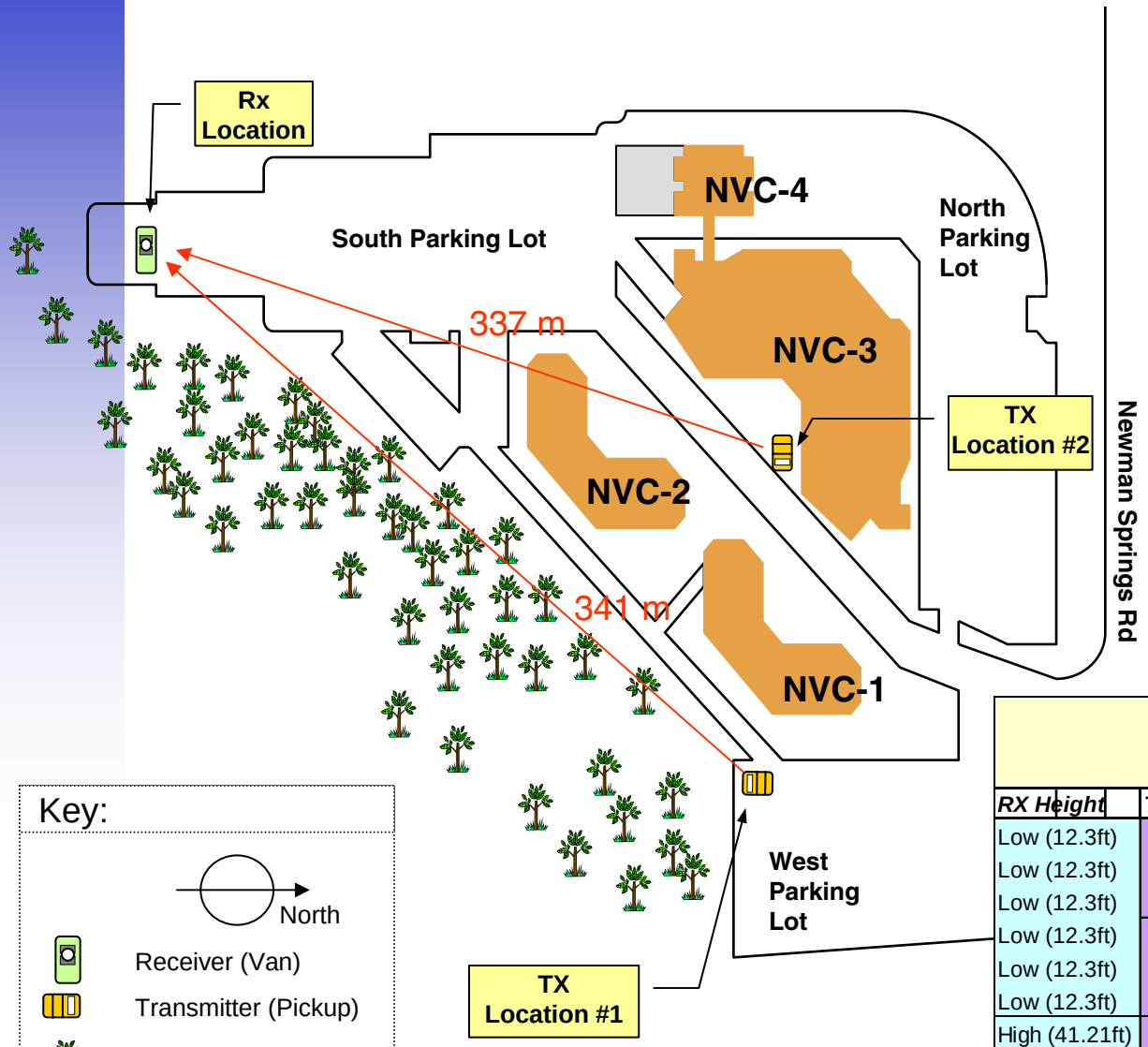
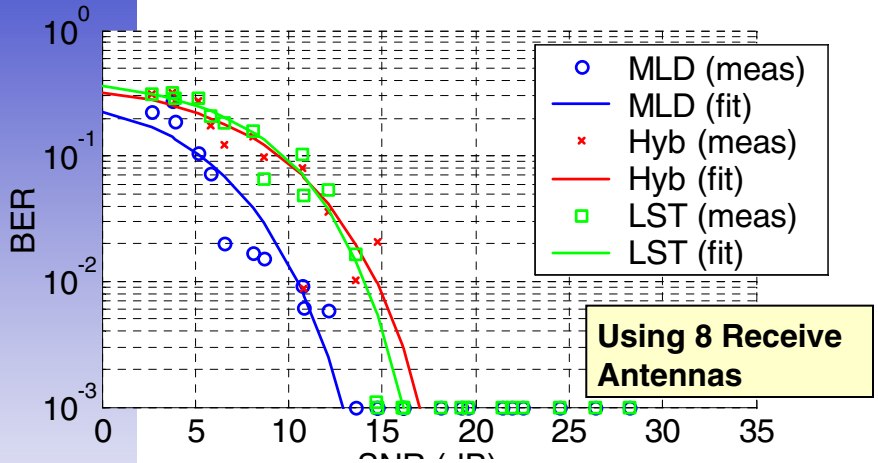
Spring 2002 Measurement Locations

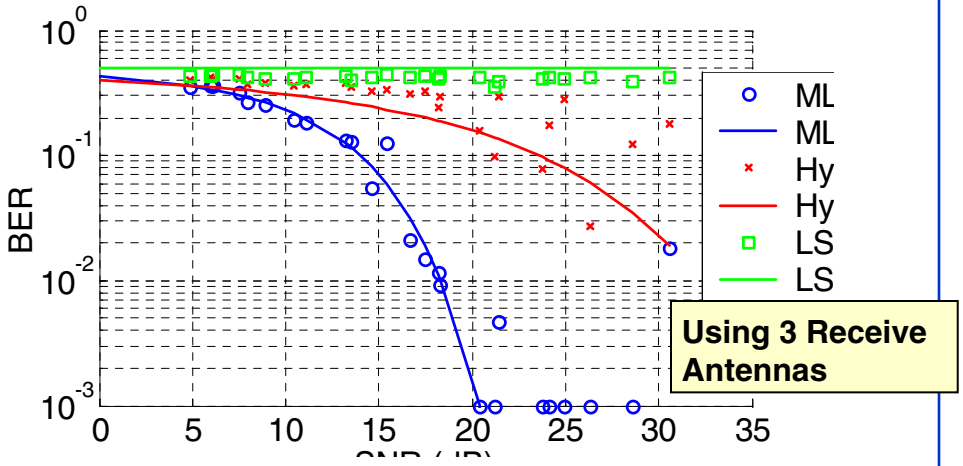


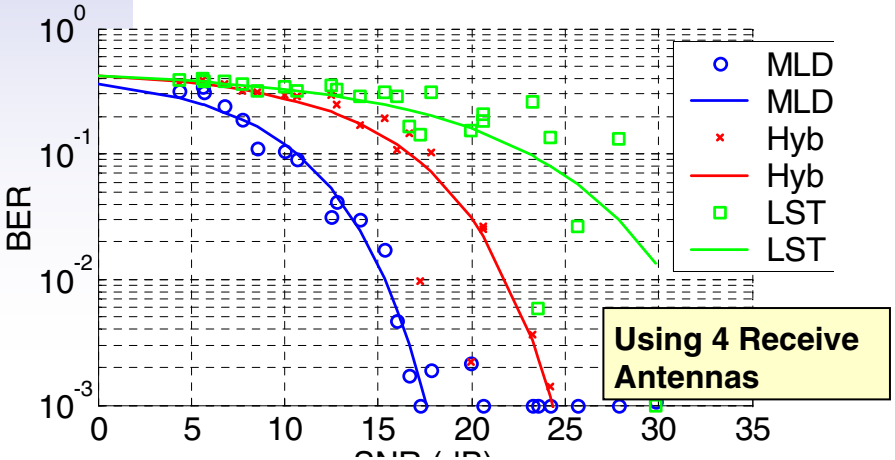
- 578 total measurements
  - 3 experimental deployments
  - 17 – 40 different SNRs for each measurement configuration
  - 3 different carrier frequencies
  - Movement of transmitter to average over a local area

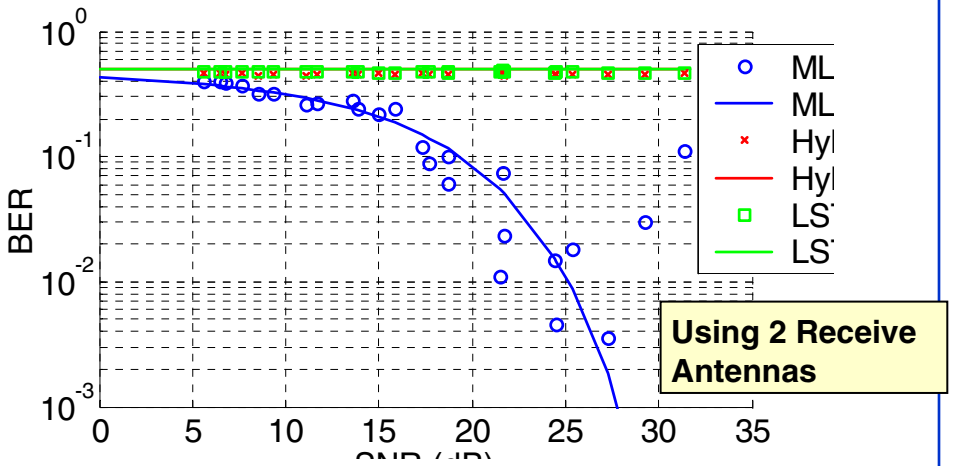
			# of Measurements (each with different transmitter power level)		
RX Height	*TX Move*	*Freq (MHz)*	Canyon 2/27/2002	Trees 2/28/2002	Canyon 3/1/2002
Low (12.3ft)	0	fc	27	40	26
Low (12.3ft)	0	fc-2 MHz	17	40	26
Low (12.3ft)	0	fc+2 MHz	17	40	26
Low (12.3ft)	+6in	fc	17	40	26
Low (12.3ft)	+6in	fc-2 MHz	17		22
Low (12.3ft)	+6in	fc+2 MHz	17		22
High (41.21ft)	0	fc	17	40	22
High (41.21ft)	+6in	fc	17	40	22

Spring 2002 OFDM STTC MIMO Measurement Results









"Canyon Measurements"

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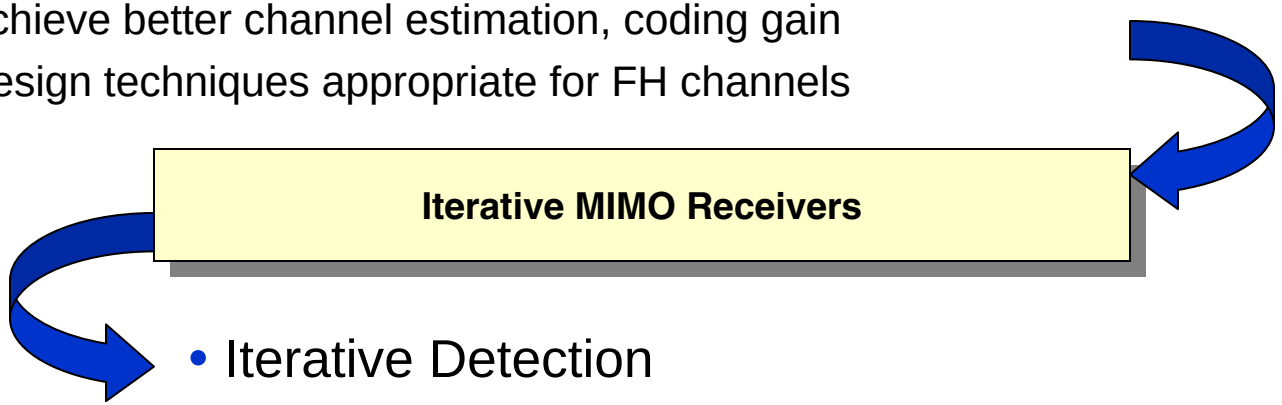
Next Steps

- In previous measurements:
  - Demonstrated value of ML detection when the number of receive antennas is limited
  - Demonstrated dynamic grouping
- Next steps
  - Design for FH compatible environments
  - Derive computationally tractable receivers
  - Achieve better channel estimation, coding gain
  - Design techniques appropriate for FH channels



- Iterative Detection
  - Iterative channel estimation
  - Double encoding + interleaving
  - Computation of LLRs
  - Sphere detection

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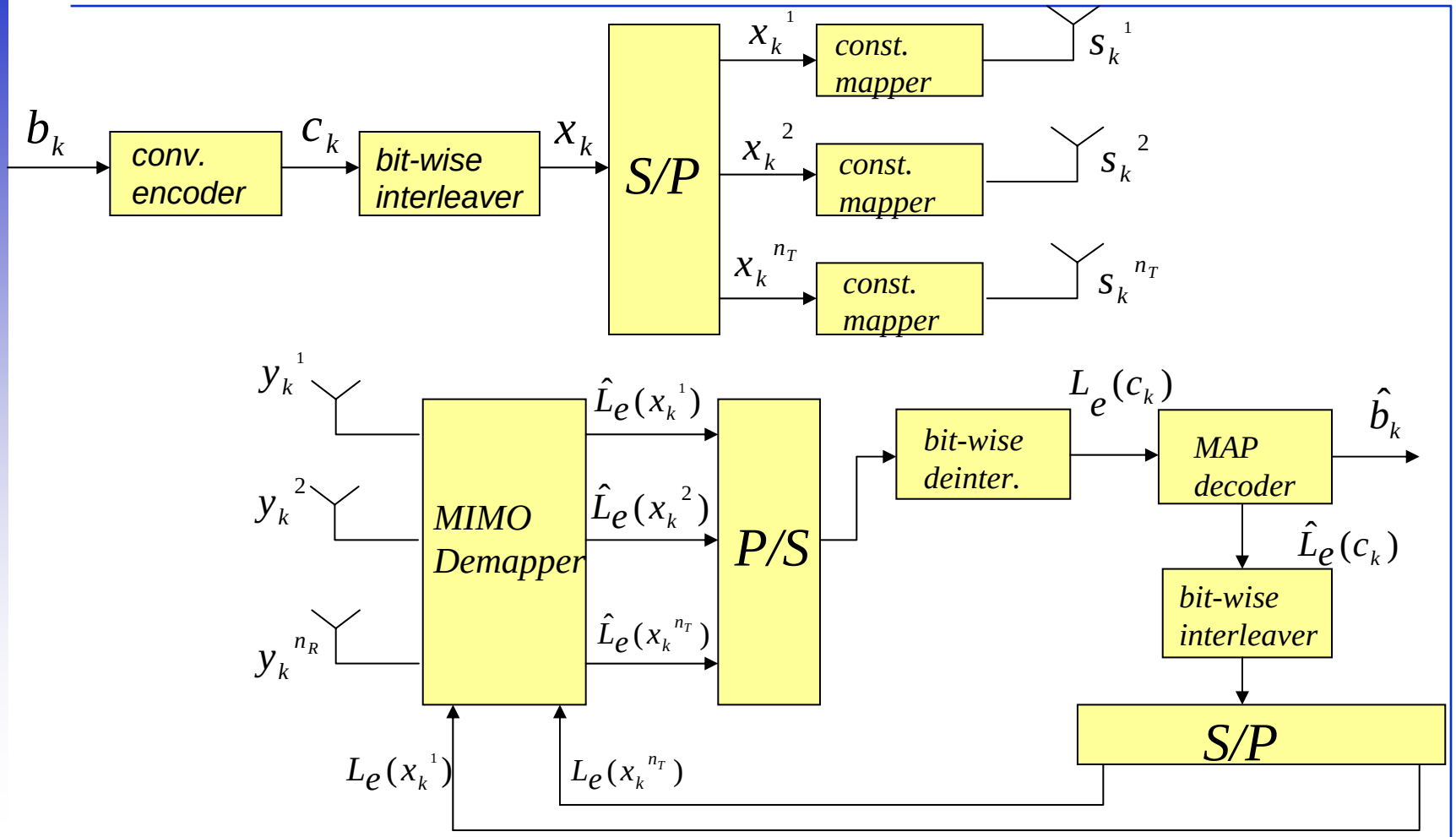
Space-Time Bit-Interleaved Coded Modulation



Ref: Stefanov and Duman, JSAC 2001
Tonello, VTC 2000 Fall

$L_e(x)$ Extrinsic LLRs

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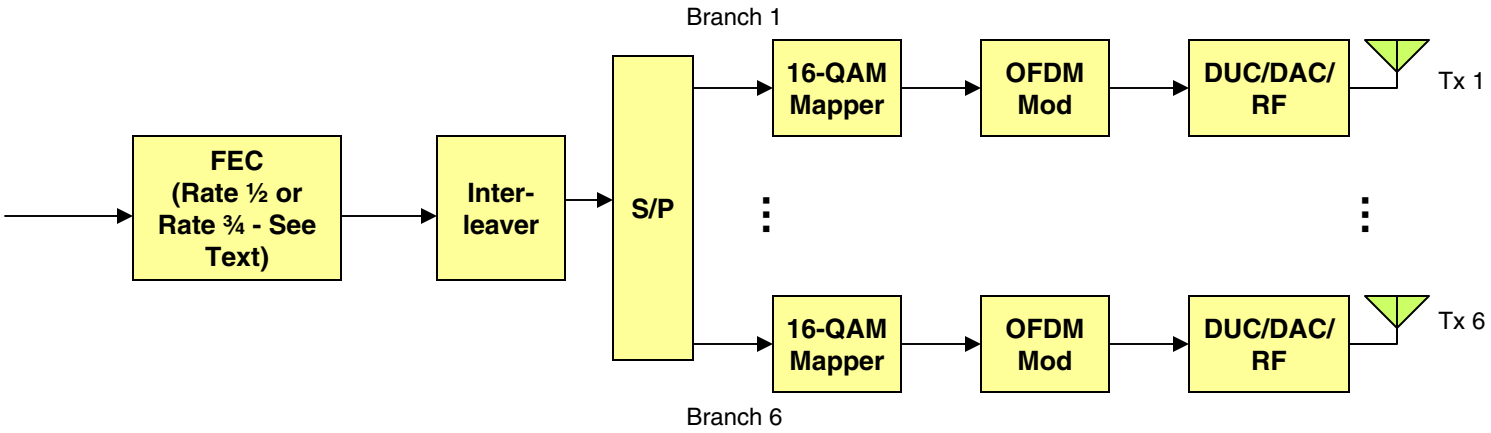
Iterative MIMO Waveform used for Summer 2003 (ST-BICOM)

- The following transmitter-receiver pair incorporates concepts from ST-BICM, but adds:
  - OFDM
  - Soft Cancellation
- System achieves information spectral efficiency of 10.3 bps/Hz using 6x8 system.



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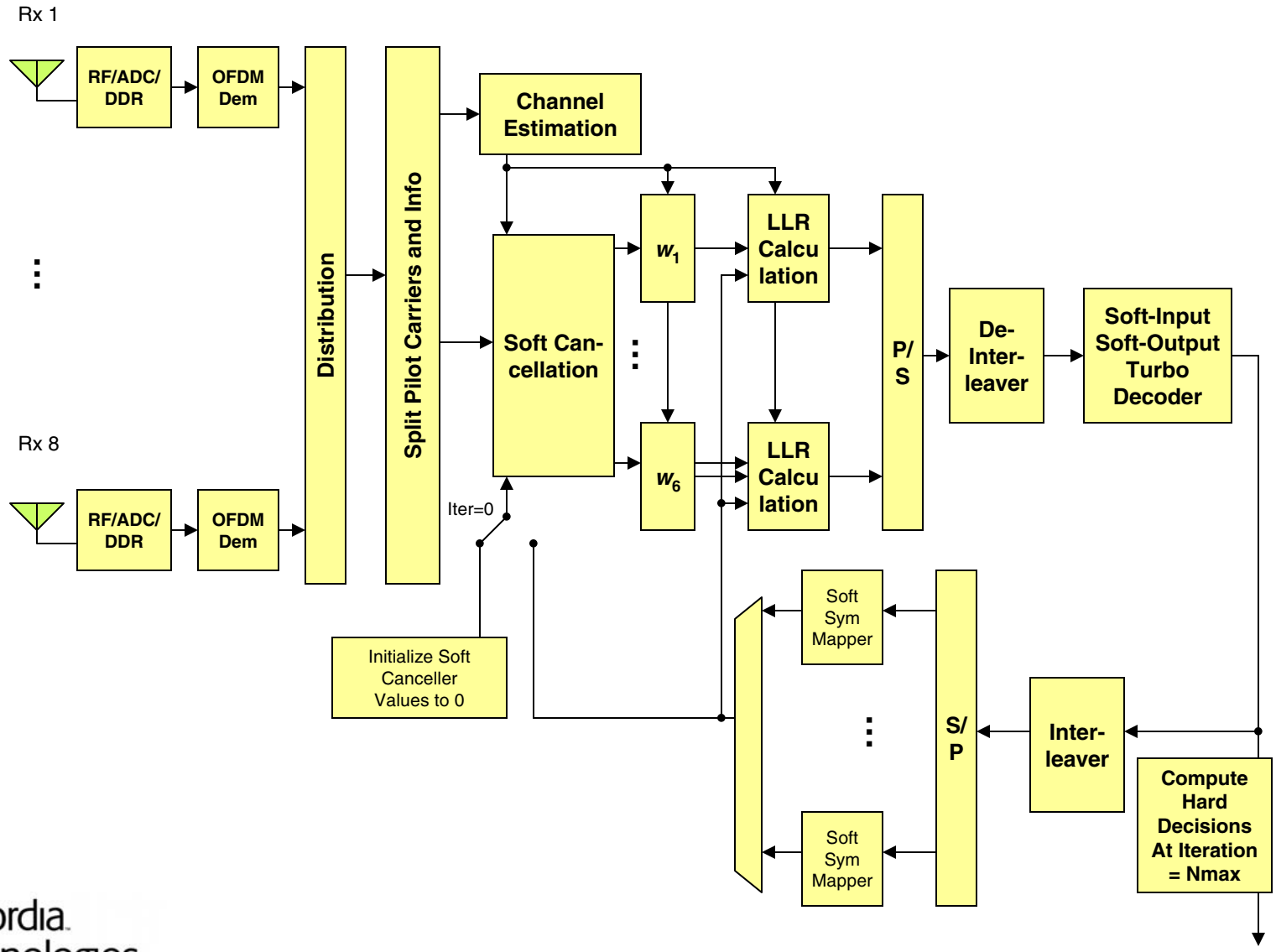
Iterative MIMO Receiver used for Summer 2003 (ST-BICOM)



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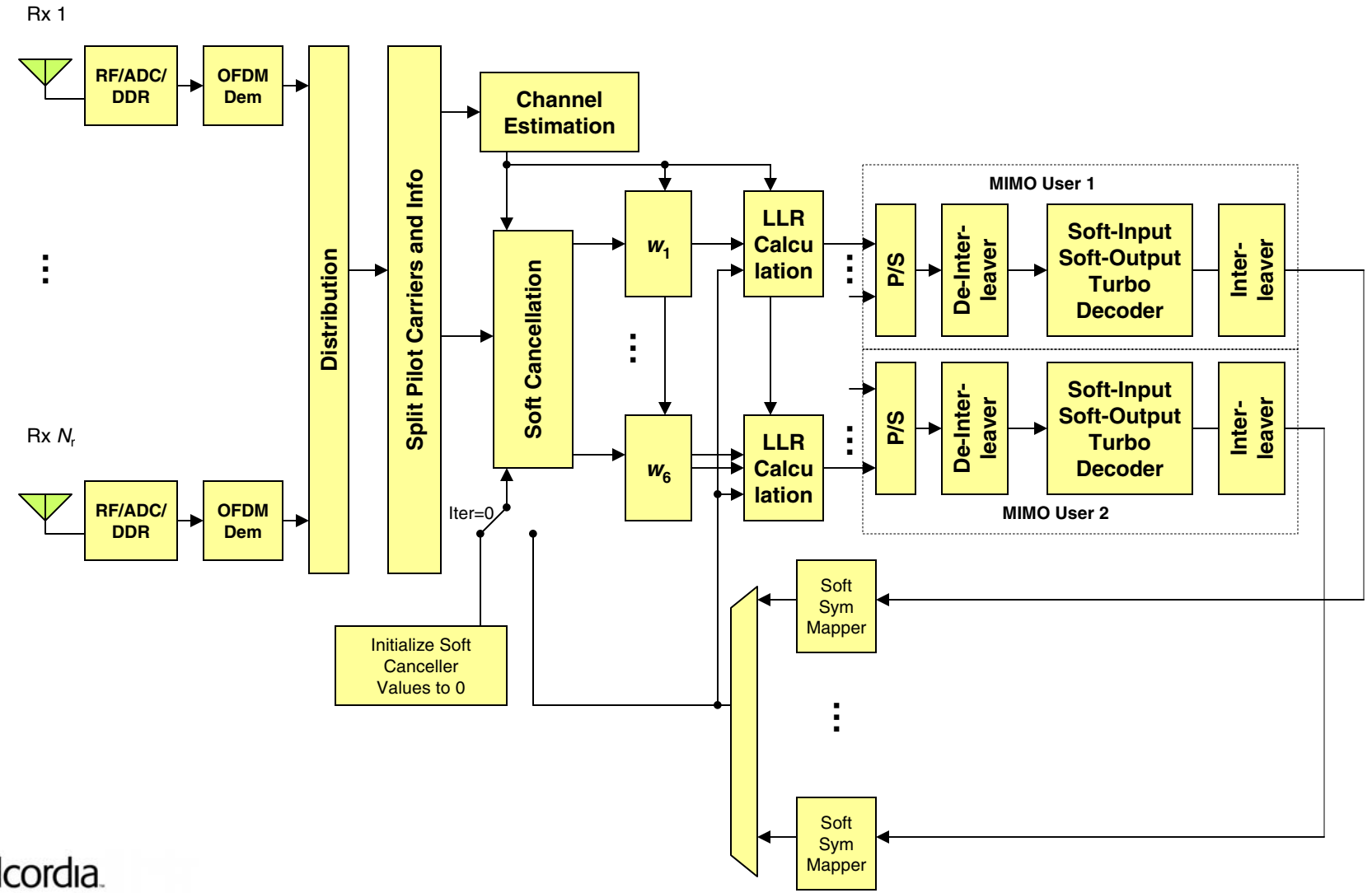
Multi-User MIMO Iterative Detector



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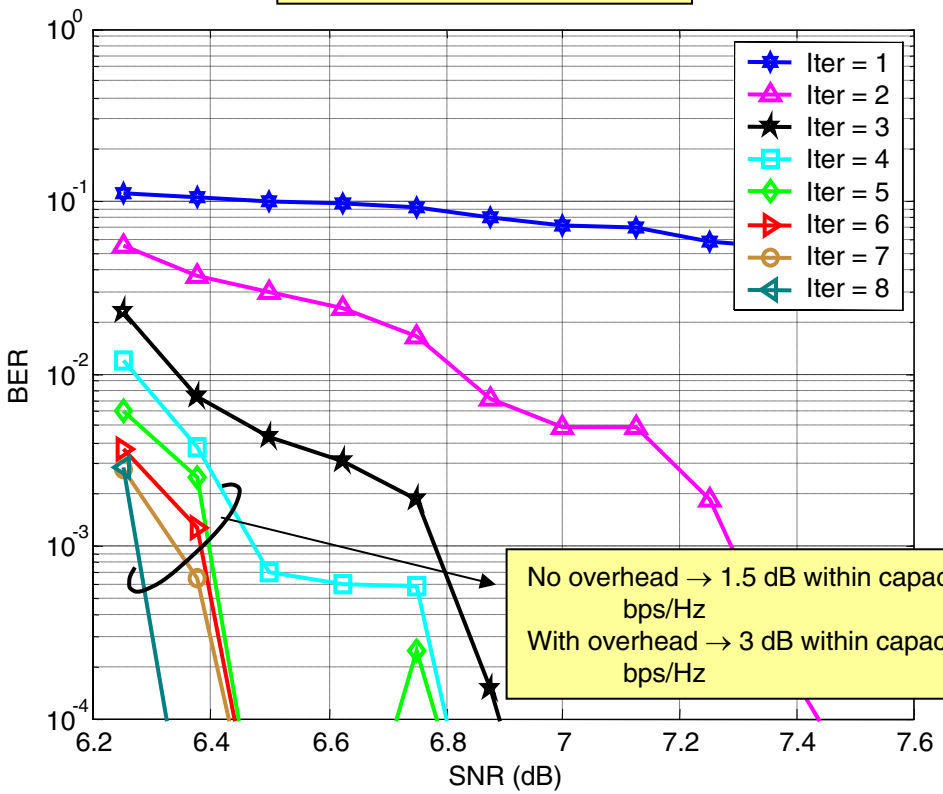
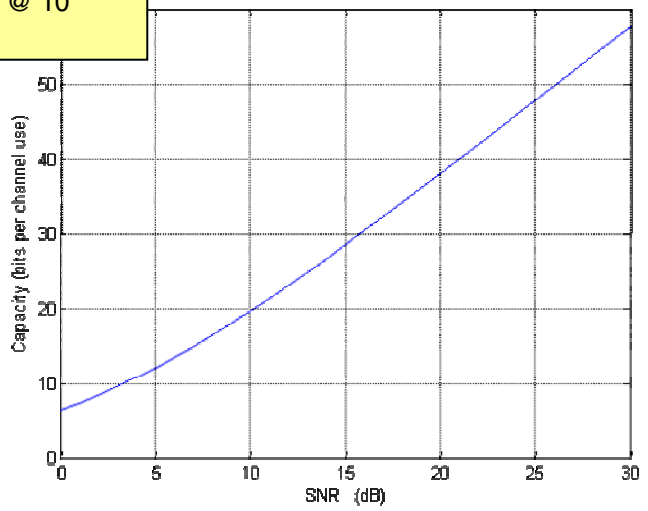
6 x 8, 16-QAM, Rate ½ Turbo (Simulation)

With Soft-Cancellation



No overhead → 1.5 dB within capacity @ 12 bps/Hz
With overhead → 3 dB within capacity @ 10 bps/Hz

Capacity (bps/Hz)	SNR (dB)
10	3.4
12	5.0



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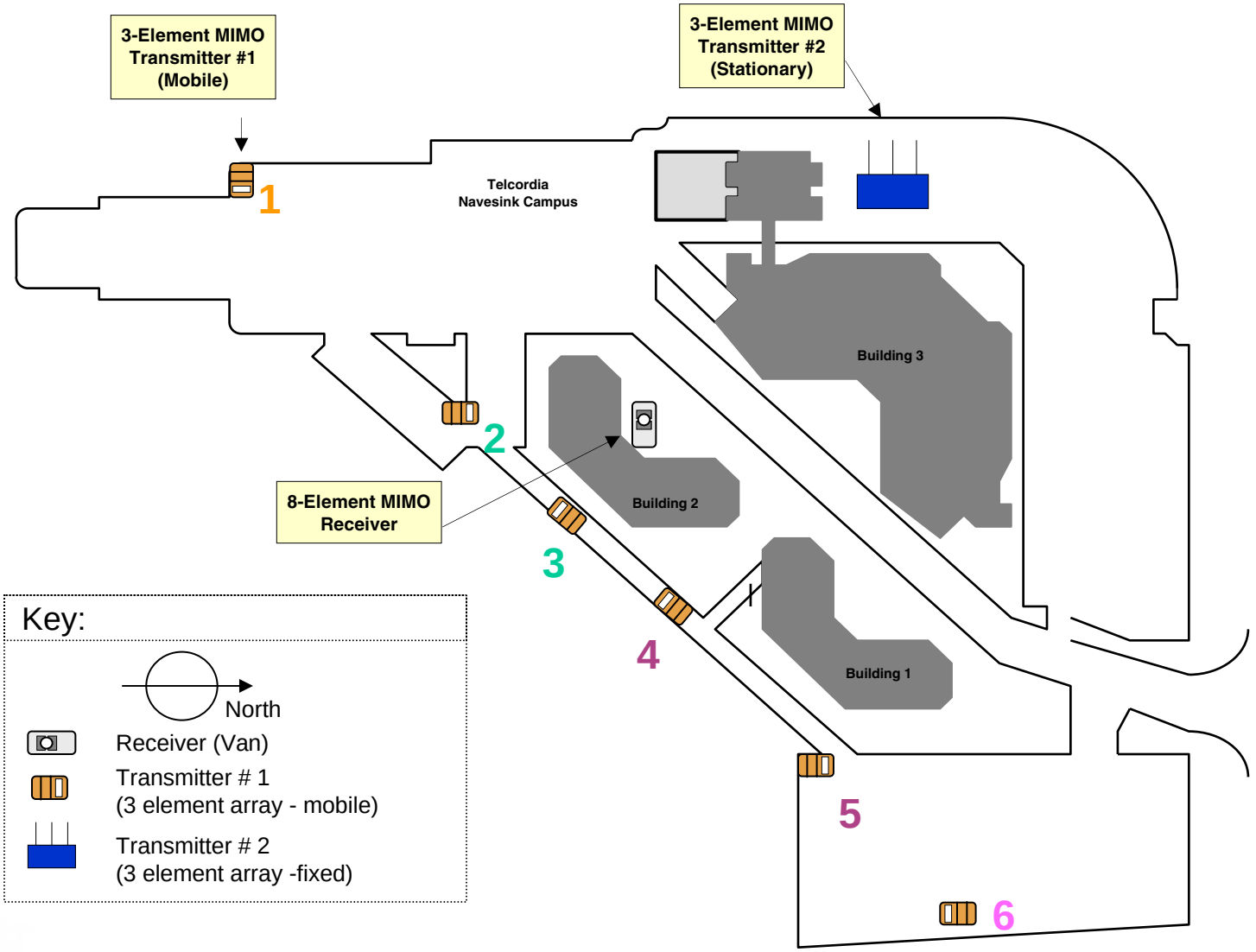
Summer 2003 Multi-User MIMO Experiments



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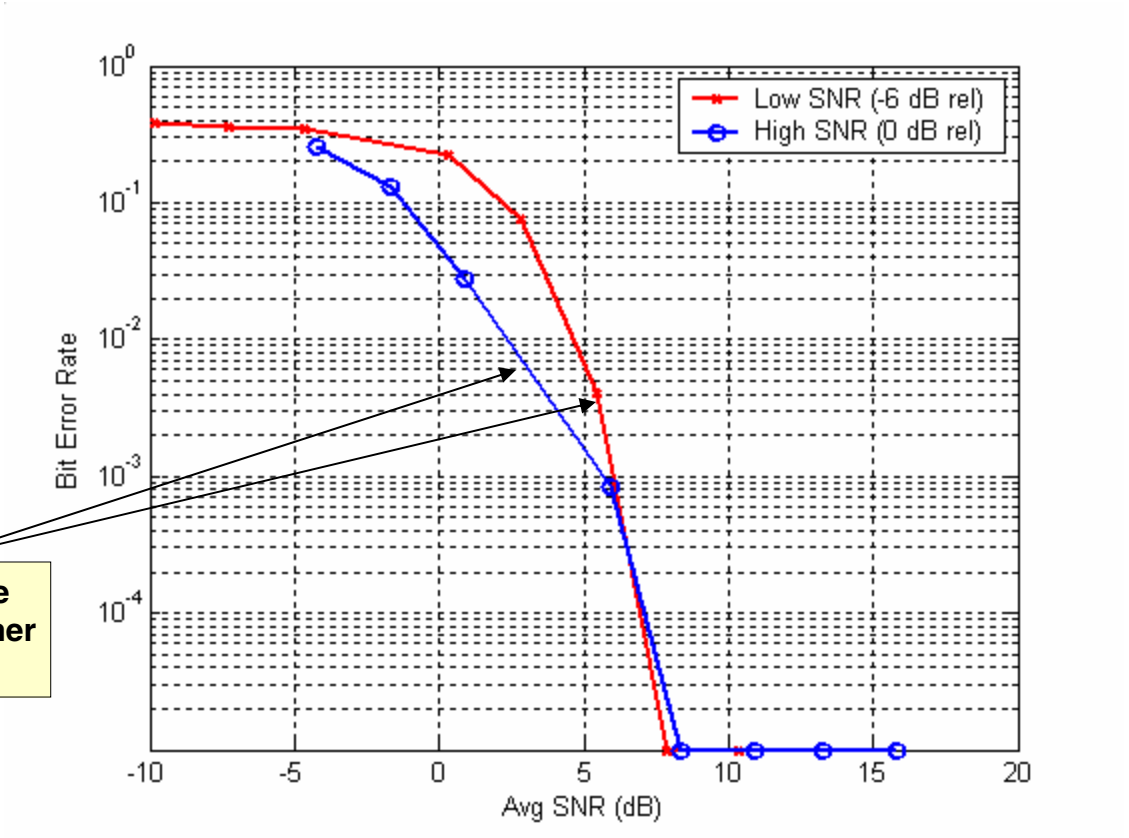
2-User Experimental Case Using Multi-User MIMO Iterative Detector

**3 Transmitters on Each MIMO Tx,
8 Antennas on the Receiver**



Low SNR User has an average SNR that is 6 dB below the higher level user.

The average SNR for each 3x Node is shown as the overall SNR is varied. The relative levels of the two users are approximately fixed.

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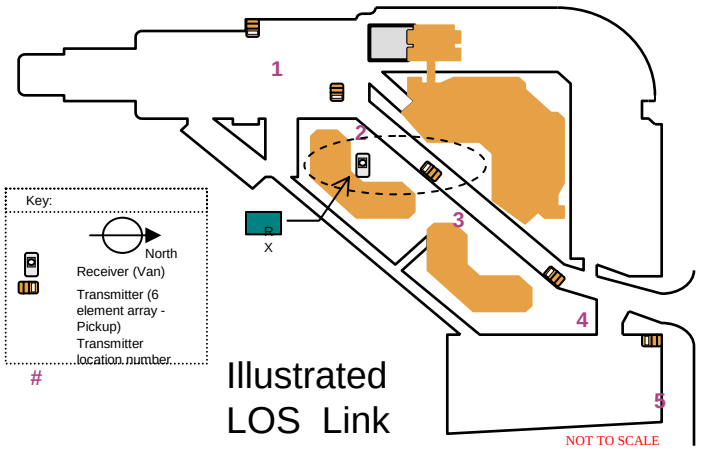
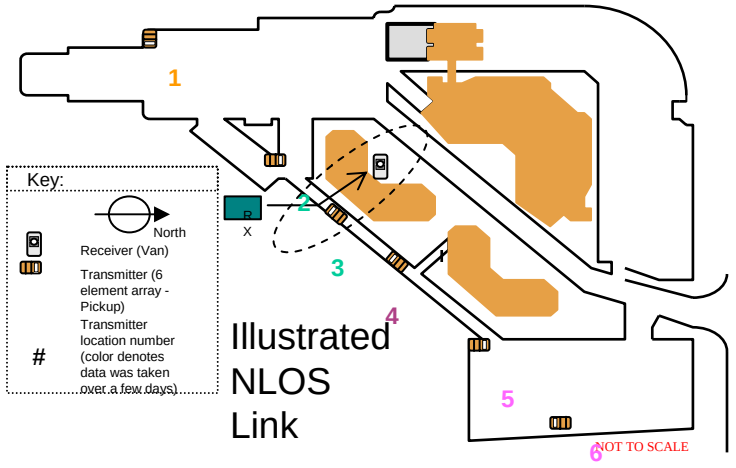
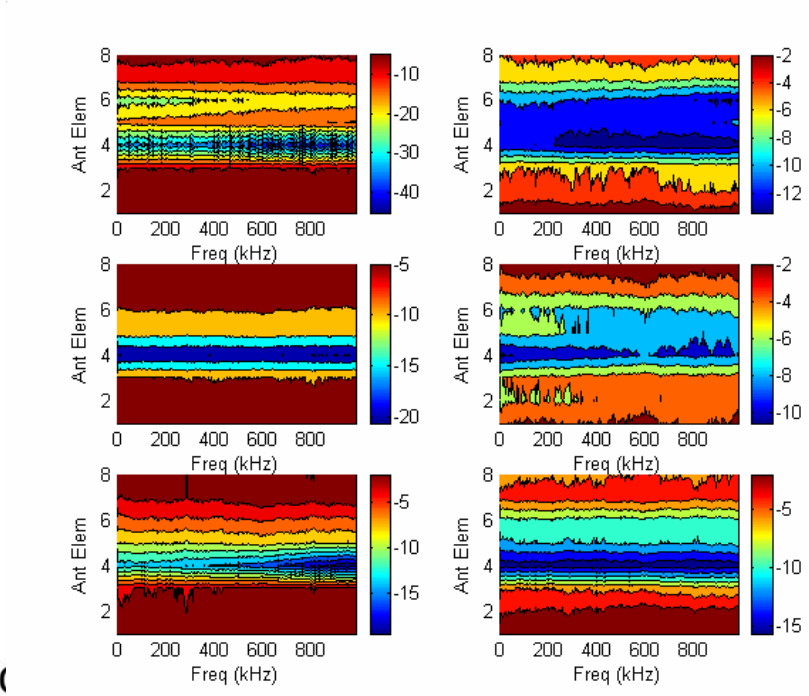
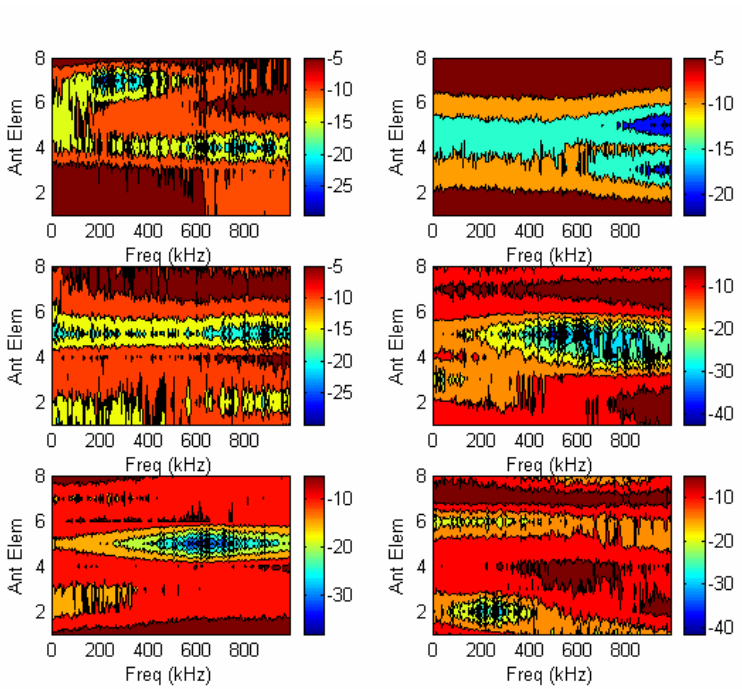
MIMO Channel Characterization









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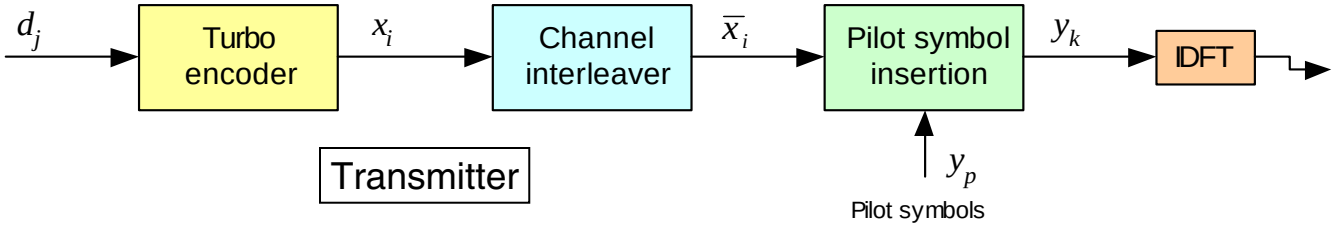
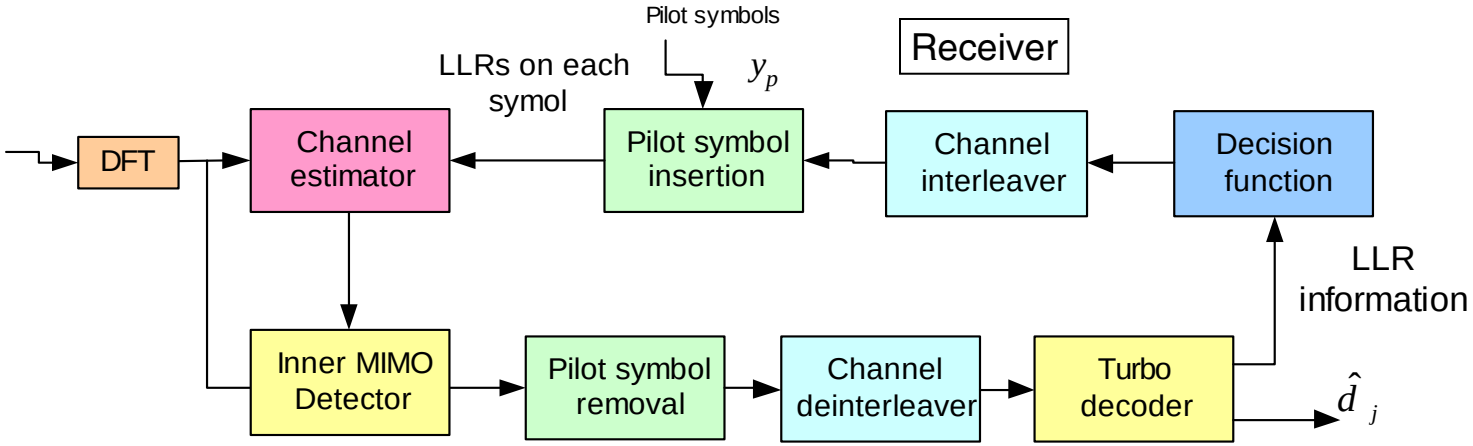
Iterative channel estimation (MIMO Case)





- Initial channel estimates are performed using pilot symbols.
- Channel estimates are improved during periods with no pilot symbols by using tentative decisions from the turbo decoder.

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Summary

- Presented Spring 2002 measurement results which demonstrated improvements using ML detection over null-and-cancel methods when the number of receive antennas is limited.
- Developed waveforms that extend Space-Time Bit Interleaved Coded Modulation (ST-BICM) to include OFDM with soft cancellation.
- Implemented a measurement campaign in Summer 2003 using the ST-BICOM-SC waveform/receiver to demonstrate high spectral efficiency coupled with low-Eb/No tolerance.